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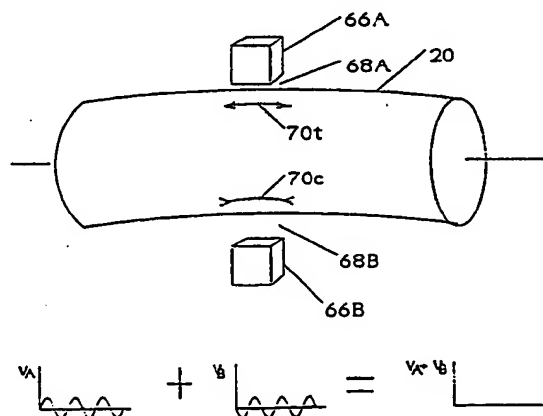
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## 54 **Magnetostrictive torque sensor.**

57 A noncontacting method for sensing torque based on the principle of magnetostriction which induces a primary magnetic flux in a shaft (20) and obtains a torque dependent secondary signal which is a function of a secondary flux is characterized by obtaining an auxiliary signal via such means as an auxiliary core/coil (48/50) and using that signal with appropriate electric circuitry to eliminate non-torque induced variations in the secondary signal. The first embodiment (Figures 5A and 5B) uses the auxiliary signal to maintain the primary magnetic flux at effectively constant amplitude. The second embodiment (Figures 6A and 6B) divides the secondary signal by the auxiliary signal. A third embodiment (Figure 7) employs a plurality of sensors (66A/66B) strategically located around the shaft (20) to eliminate spurious signals which are due to bending stress and shaft misalignment.



**FIGURE 7**

## Description

## MAGNETOSTRICTIVE TORQUE SENSOR

## BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to a torque sensor based on the principle of magnetostriction, and more particularly, to an improved magnetostrictive torque sensor which is simpler, more accurate, and more economical than state of the art sensors as well as more suitable to mass production and usage.

Description of Prior Art

Engineers and scientists have sought a simple, reliable, accurate means for measuring torque in rotating shafts for well over a century. Applications for such a torque measuring apparatus include diagnosis, prognosis, and load level monitoring of a vast number of different types of rotary drive mechanisms such as automotive, ship, and plane engines; motors and generators of all types; oil drilling rigs; rotating machining tools; all electric power steering; robotics; and much more.

Further, measurement of mechanical power produced by an engine (or used by a generator) cannot be made without knowing both torque and rotational speed of the shaft. Hence there has heretofore been no ready means to determine on-line power and efficiency of rotary drive devices simply, accurately, and reliably. This has proven to be problematic in many areas of modern technology, but it has been particularly troublesome in attempts to develop modern automotive engine control systems which would improve fuel efficiency and optimize engine performance.

Heretofore several methods have been developed for measuring torque in rotating shafts (see below), but none has been ideal. That is, no single presently known method offers all of the following desirable properties.

1. Contact free (no slip rings, etc.)
2. Reliable (low failure rate)
3. Accurate
4. Small and unobtrusive (requiring little shaft/engine re-work)
5. Inexpensive
6. Applicable at high as well as low speeds
7. Instantaneous torque measurement (not merely mean torque over several revolutions)
8. Amenable to mass production (not restricted to special test apparatus)

There are presently only four distinct methods for measuring torque directly in a rotating shaft. They are:

1. Twist angle of shaft measurement
2. Strain gauge sensor
3. Reaction force measurement
4. Magnetostrictive sensors

The twist angle method involves measurement of the angle of twist of a shaft and correlates this, using the material and dimensional characteristics of the shaft, to torque. It entails a complicated and cumbersome mechanism with low sensitivity, calibration difficulties, and the necessity of using two different locations along the shaft. It invariably entails extensive engine modification, a costly endeavor.

The strain gauge approach requires bonding of strain gauges to the shaft surface and relating strain measurement to torque. It is limited to low speed, is not amenable to mass production, lacks durability, and needs some means such as slip rings and brushes to bring the signal off of the shaft.

Reaction force measurement utilizes Newton's second law for rotational motion to relate force and motion of the engine mounts to shaft torque. The method must employ a large structure, has low sensitivity, is not feasible for production runs, and measures driveline, not engine, torque.

Magnetostrictive torque sensors take advantage of the magnetostrictive property of ferromagnetic materials whereby tension stress increases (and compressive stress decreases) a given magnetic induction field (i.e., the "B" field) carried by the material. A coil of wire of arbitrary number of turns wrapped around an iron core is placed close to the shaft and an electric current passing through the wire causes a magnetic field to be induced in the rotating shaft. In magnetostrictive sensor designs such as those described in U.S. Patents 2,912,642 and 4,589,290 a second coil of arbitrary number of turns wrapped around a second iron core is then placed close to the shaft and used to measure the change in the induction (the B field) which results from the increased surface stress caused by the applied torque.

The magnetostrictive method has several advantages over the other three methods, including

- 1) Non-contact: no slip rings

- 2) Not restricted to low speeds
  - 3) Measures torque of engine directly
  - 4) High sensitivity
  - 5) Economical
  - 6) Simple structure: no strain gauges, no large apparatus 5
  - 7) Only one location anywhere on shaft: little engine rework
  - 8) Durable and reliable: no moving parts to cause mechanical failure, resistant to high pressure and temperature of engine environment
  - 9) Readily miniaturized: can be made unobtrusive
- However, magnetostrictive torque sensors have heretofore been plagued with several major problems which have prevented them from becoming the standard in the field. These are 10
- 1) Output signal varies with RPM even at constant torque.
  - 2) Output signal varies with temperature.
  - 3) Spurious signal variation within one mechanical cycle (one revolution of shaft) prohibits accurate instantaneous measurement of torque: only average values over several shaft revolutions are possible. 15
  - 4) Correction methodologies such as those described in U.S. Patents 4,589,290 and 4,697,459 and SAE paper #870472 heretofore employed for problems 1) to 3) above have not been able to reduce inaccuracies to an acceptable level.
  - 5) All such correction methodologies developed to date involve complicated and extensive electronic circuitry and/or additional sensors for temperature and RPM. 20
  - 6) Additionally, all such correction methodologies utilized to date are affected by subtle individual shaft material and property variations such as residual stress, slight inhomogeneity in shaft magnetic properties, shaft tolerances/misalignment, and shaft bending stress. Hence such methodologies must be tailored specifically for each individual shaft and therefore are not suitable for mass production.
  - 7) Furthermore, such correction methodologies have to be re-calibrated repeatedly over the lifetime of the shaft, since residual stress values, tolerances, misalignments, bending stresses, and even magnetic property inhomogeneities change over time (particularly in high temperature environments such as those of automobile engines.) Recalibration for mechanisms such as automobile engines is so difficult as to render such correction methodologies impractical. 25

### OBJECTS AND ADVANTAGES OF THIS INVENTION

- Accordingly, several general objects and advantages of this magnetostrictive torque sensor invention over prior art are considerable improvement in accuracy to well within acceptable levels, simplicity of design, lowered cost, suitability for mass production, and practicality for continued usage. Such general objects and advantages are achieved by the following specific objects and advantages. 35
- 1) Elimination of signal dependence on shaft rotation speed.
  - 2) Elimination of signal dependence on temperature.
  - 3) Elimination of signal variations within a single shaft revolution due to shaft magnetic property inhomogeneities and residual stresses. 40
  - 4) Elimination of signal variations due to bending stress, shaft misalignment, and tolerance variations.
  - 5) Instantaneous measurement of torque resulting from advantages 3) and 4) above.
  - 6) Elimination of signal dependence on individual shaft properties and hence suitability for mass production. 45
  - 7) Elimination of need to recalibrate sensing device during course of shaft lifetime.
  - 8) Simple, effective signal processing circuitry and sensor orientation permitting advantages 1) through 7) above.

Further objects and advantages of the invention will become apparent from a consideration of the drawings and ensuing description of it. 50

### SUMMARY OF THE INVENTION

This magnetostrictive torque sensor invention solves essentially all of the problems associated with prior art through heretofore unrealized insight into the fundamental electromechanical principles underlying previous experimental results and by using that insight to devise a superior design solution. 55

In prior art a coil of wire with current flowing through it induces a primary magnetic induction field (B field) in a ferromagnetic shaft which is located close to the coil. If the shaft is not moving, a constant amplitude AC current in the wire will produce a constant amplitude magnetic flux in the shaft where the flux amplitude depends on the magnetic permeability of the shaft material. As torque is applied to the shaft, the shaft experiences torsional stress as a result of the applied torque. Through the phenomenon of magnetostriction, a secondary magnetic induction field component arises at an angle to the primary magnetic field direction and the magnitude of that second magnetic field flux is dependent on the amount of torque applied to the shaft. The secondary flux is measured via Faraday's law by placing a second coil close to the shaft aligned in the 60 65

direction of the secondary magnetic field and then measuring the voltage across the second coil. The voltage across the second coil is therefore a direct indicator of torque. The procedure is accurate if the primary field flux can be maintained constant.

If the shaft is turning, however, and if the shaft has local variations in permeability around its circumference (true of virtually all shafts), then the flux amplitude in the shaft is not constant and varies as the shaft turns.

A different shaft, with different permeability, will also result in different primary magnetic flux, yielding a different voltage across the secondary coil, and hence prohibiting use of the sensor on a mass production scale.

This problem is solved in the present invention by using an auxiliary coil (i.e., a third coil) to measure the primary magnetic flux via Faraday's law. Feedback of the signal from the auxiliary coil to the power supply for the primary coil is done in such a manner as to maintain the auxiliary coil voltage amplitude constant, thereby maintaining the primary flux amplitude constant regardless of changes in shaft permeability due to rotation of a single shaft or use of different shafts. Hence the torque indicating output signal from the second voltage will be independent of shaft speed or shaft material composition.

A second embodiment of the invention divides the secondary coil voltage by the auxiliary coil voltage to obtain a signal which has a similar integrity. The second coil voltage varies with RPM, shaft material, and torque whereas the auxiliary coil voltage varies with RPM and shaft material, but not torque. Hence the resultant signal after division is free of spurious signal components and is an accurate indication of torque.

Embodiment three employs two or more magnetostrictive torque sensors of any of embodiments one through four by placing the sensors strategically around the shaft such that a resultant signal produced by combining the signals of the individual sensors is free of erroneous signal components resulting from bending or misalignment of the shaft.

The invention, in its various embodiments, solves each of the problems associated with prior art discussed in the "Description of Prior Art" section in a superior and wholly satisfactory manner.

## BRIEF DESCRIPTION OF THE DRAWINGS

### Drawings Illustrating Prior Art

Figs. 1A and 1B depict the behavior of an induced magnetic field B in a shaft undergoing applied torque. Fig. 1A depicts the zero torque state; Fig. 1B the state with applied torque.

Figs. 2A and 2B show the standard prior art configuration magnetostrictive torque sensor. Fig. 2A depicts the physical arrangement of the primary and secondary coil/cores; Fig. 2B depicts the signal processor circuit block diagram.

### Drawings Illustrating Problems and Limitations of Prior Art

Fig. 3 is a reproduction from SAE paper #870472 showing the signal variation in output signal with constant torque over one mechanical cycle which is typical of prior art configurations.

Fig. 4 is also a reproduction from SAE paper #870472 and shows the variation in output signal with shaft rotation speed which is found in prior art configurations.

### Drawings Illustrating the Present Invention

Fig. 5A depicts the signal processor block diagram representing one variation of embodiment number one of the present invention. Fig. 5B shows a second variation of embodiment number one.

Fig. 6A depicts the signal processor block diagram representing one variation of embodiment number two of the present invention. Fig. 6B shows a second variation of embodiment number two.

Fig. 7 depicts embodiment number three of the present invention, comprising a multiplicity of magnetostrictive torque sensors strategically located such that the sum of the voltages produced by each sensor is a signal which is effectively free of misalignment and bending stress induced signals.

## DRAWING REFERENCE NUMBERS

20 rotating shaft

30 primary core	
32 primary coil	
34 secondary (pickup) core	
36 secondary (pickup) coil	
38 voltmeter measuring output of secondary coil	5
40 oscillator	
42 power amplifier	
44 amp meter	
46 low pass filter	
48 auxiliary coil (on primary core)	10
50 auxiliary coil voltmeter	
52 auxiliary coil (on primary core) for embodiment number two	
54 auxiliary coil voltmeter for embodiment number two	
56 signal divider	
66A magnetostrictive sensor A	15
66B magnetostrictive sensor B, on opposite side of shaft	
68A air gap between sensor A (item 66A) and shaft (item 20)	
68B air gap between sensor B (item 66B) and shaft (item 20)	
70c bending compressive stress	
70t bending tensile stress	20

## PRINCIPLES AND ANALYSIS OF MAGNETOSTRICTIVE TORQUE SENSORS

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### Conceptual Overview

Figures 1A and 1B show the effect on an induced magnetic field (also called induction) B in a shaft 20 when torque is applied to the shaft 20. Figure 1A depicts the shaft 20 with zero torque applied and the induction B directed circumferentially. The induction B can also be represented in terms of two components  $B_x$  and  $B_y$  at 45° angles to the circumferential direction.

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Figure 1B illustrates the change in the induction B when torque is applied. The torque creates tensile stress  $\sigma_t$  in the direction of the induction component  $B_x$ , and compressive stress  $\sigma_c$  in the direction of the induction component  $B_y$ . Due to the principle of magnetostriction, induction component  $B_x$  increases in magnitude to  $B'_x$ ; and induction component  $B_y$  decreases in magnitude to  $B'_y$ . The induction components can then be added vectorially to obtain the induction with torque applied  $B'$ . The induction  $B'$  makes an angle  $\delta$  with respect to the original induction B, and can then be represented in terms of two components  $B'_{circ}$  and  $B'_{axial}$  directed along the circumferential and axial directions respectively. Therefore,

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$$B'_{circ} = B' \cos \delta$$

$$B'_{axial} = B' \sin \delta.$$

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The angle  $\delta$  is in practice quite small, hence

$$B'_{circ} \approx B' \approx B$$

$$B'_{axial} \approx B' \delta \approx B \delta.$$

The magnitude of  $B'_{axial}$  increases with increasing applied torque and equals zero when torque equals zero.

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Figures 2A and 2B depict the standard prior art configuration for inducing the magnetic induction B and for measuring the induced axial induction  $B'_{axial}$ . Figure 2A shows the primary coil 32 carrying current, typically AC, wrapped around the primary ferromagnetic U shaped core 30 in which the core 30 is aligned circumferentially to shaft 20 and in which the ends of the core 30 are shaped and placed such that a constant width air gap exists between the core 30 and the shaft 20. The current in primary coil 32 causes a magnetic flux to be carried through primary core 30 across the air gaps and along the surface of shaft 20 in a manner similar to that depicted in Figures 1A and 1B.

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Secondary coil 36 is typically open circuit and is wound around secondary U shaped core 34 which is aligned in the axial direction of shaft 20 and has ends shaped and oriented such that constant width air gaps exist between the secondary core 34 and the shaft 20. Application of torque to the shaft when current is passing through the primary coil 32 causes axial induction  $B'_{axial}$  to arise and magnetic flux to pass through secondary core 34. Voltage is then produced in secondary coil 36 via Faraday's law and measured by voltmeter 38. This voltage is zero for zero applied torque and increases as torque increases; hence, the voltage is a direct measure of applied torque.

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### Limitations of Idealized Approach

Figure 3 is a reproduction from SAE paper #870472 showing the spurious output signal variation measured by voltmeter 38 (see Figure 2B) within each single revolution (mechanical cycle) of shaft 20.

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This phenomenon is attributed to local variations in magnetic permeability and residual stress around the shaft circumference. The shaft material is not completely homogeneous either in its magnetic properties or in degree and distribution of residual stresses. As the shaft rotates, these non-uniformities pass under the sensor and alter the amount of flux transmitted through the sensor coils. The result is a non-torque dependent variation in the output voltage.

A second cause for spurious subcycle signal alteration is variation in air gap thickness between sensor and shaft due to i) shaft misalignment and/or ii) bending stresses in the shaft. Since the flux is also dependent on this gap thickness, if the gap thickness varies then so will the output voltage.

The standard solution to this problem has been to use a low pass filter to eliminate all signal variations with frequencies greater than that of one shaft revolution (one mechanical cycle.) Unfortunately, this introduces a time constant into the device which limits the measurement bandwidth to approximately 1/2 the mechanical frequency and precludes measurement of torque changes more rapid than those occurring over several mechanical cycles. The resulting signal becomes an average rather than an instantaneous measure of torque and is hence limited to steady state or slow transient operations.

Figure 4 is also a reproduction from SAE paper #870472 and illustrates a second problem encountered in prior art - the variation in output signal with RPM. Increasing the speed of rotation of the shaft while torque remains constant increases the output signal. This is undesirable since the ideal signal should reflect change in torque alone. The common solution approach heretofore employed has been to monitor RPM and introduce a shaft speed dependent correction to the output signal detected by voltmeter 38. This has not been completely successful, eliminating some but not all of the error. Further, it has complicated the device by introducing additional measurement and apparatus.

A third problem in prior art is temperature dependence. As the shaft temperature varies (a common phenomenon in automobile and many other engines), so does the output signal even as all other parameters remain constant. This is no doubt due in large part to i) temperature induced variations in magnetic permeabilities of the shaft/sensor materials, ii) concomitant modification in tolerances which affect the air gap dimension between sensor and shaft, and iii) changes in resistivity of the wires used in the sensor. The typical prior art solution is to employ feedback from a thermocouple to further correct the output signal. As reported in SAE paper #870472 this also has had only some but not full success. This is presumably because different temperature gradation fields within the engine would affect the sensor/shaft differently yet could have the same temperature value for any given single point (i.e., the point at which the thermocouple might be located.)

Signal instability or drift over time is yet a further problem. During testing, the SAE paper #870472 researchers found it necessary to "null out" the zero torque signal anew each day. In summary, several disadvantages of prior art magnetostrictive torque sensors are:

a) Signal variation within one mechanical cycle prohibits accurate instantaneous torque measurement.

Average values over several cycles must be used. Causes are:

i) Local random variations in magnetic material properties

ii) Sinusoidal variation in air gap due to

- shaft misalignment

- bending stresses in shaft

b) Signal drifts from day to day

c) Output varies with RPM

d) Output varies with temperature

#### Analysis of Prior Art Limitations

Faraday's law of electromagnetism, i.e.,

$$v = -N \frac{d\phi}{dt} = -NA \frac{dB}{dt} \quad (I)$$

where  $\phi$  is magnetic flux and A is core cross sectional area, can be rewritten using the definition for inductance L of a coil/core, i.e.,

$$N\phi = Li \quad (II)$$

where N is number of coil windings and i is current in the coil.

Hence Faraday's law can be rewritten as

$$v = - \frac{d(Li)}{dt} = -L \frac{di}{dt} - i \frac{dL}{dt} \quad (III)$$

In virtually all electric circuit applications L is constant and the second term in the far right hand side of (III) above vanishes. In the present case, however, it does not vanish, and as is shown below, the second term gives rise to the phenomenon of output signal dependence on RPM depicted in Figure 4.

Inductance L depends on magnetic permeability  $\mu_F$  of the shaft, and permeability varies slightly in different places around the shaft circumference. This variation can be due to either i) natural changes in the material grain structure, composition, etc. or ii) residual stresses on the shaft surface from machining, forming, etc.

(which change  $\mu_r$  via magnetostriction). Hence, as the shaft rotates, the sensor "sees" a varying inductance through which its flux must pass. The time derivative of  $L$  is therefore *not* zero and the second term in the far right hand side of (II) above becomes important, i.e., it makes a contribution to the output voltage. Further, since the time derivative reflects the rate of change of  $L$ , the time derivative increases in magnitude for increasing values of RPM. Hence, the RMS value of the second term in the right hand side of (III) increases with increasing rotational speed of the shaft, whereas the RMS value of the first term alone does not.

It is the second term which is responsible for the heretofore unexplained variation in signal output with shaft RPM. In addition, as discussed previously, the second term is also partly responsible for the irregular variation in signal within one shaft revolution shown in Figure 3.

Additionally, it is the second term which causes each individual shaft to have a different dependence on RPM, since each shaft has different local variations in residual stress and magnetic permeability. Hence correction methodologies such as those heretofore employed which attempt to correct for output signal dependence via preset feedback signal correction are not suitable for mass production. Further, the correction needed for each individual shaft will change with time as residual stresses relax and as temperature and stress alterations modify local permeability variations. Hence the heretofore used correction methodologies would become increasingly inaccurate over time and would need continual recalibration. This is impractical in most applications, but particularly so for automotive and other vehicle engines.

Conclusion: Local variations in permeability and residual stresses result in:

- a) Signal irregularities within one shaft revolution which must be "averaged out" over several cycles.
- b) Increase in output signal with RPM.

Correction methodologies used heretofore are unsuitable for mass production and become increasingly inaccurate over time.

#### DETAILED DESCRIPTION OF THE INVENTION

Previous art has maintained a long held tradition in electromechanics. That is, it has used an electronic feedback loop to keep input current  $i_p$  to primary coil 32 at a constant RMS value. The objective in doing this has been to keep primary core 30 flux  $\phi_p$  at constant RMS (see (II)). The underlying assumption is that  $L$ , the inductance, remains constant. In the case of magnetostrictive torque sensors, however, the inductance  $L$  does not remain constant, so flux  $\phi_p$  varies even if  $i_p$  remains fixed. This results in the spurious output voltage signal discussed in previous sections. The present invention, in different embodiments, involves alternative methodologies which solve this and other problems associated with prior art.

#### Embodiment 1: Feedback to keep $\phi_p$ RMS constant

Figure 5A depicts circuitry to be used with the magnetostrictive torque sensing apparatus of Figure 2A in lieu of the signal processor of Figure 2B. The volt meter 50 measures open circuit voltage in an auxiliary coil 48 of any number of turns which in addition to primary coil 32 is also wrapped around the primary core 30. From Faraday's Law (I) the voltmeter 50 can be used to measure flux  $\phi_p$  in the primary core 30. Flux  $\phi_p$  in the primary coil 32 can be monitored and used in a feedback to the power amplifier 42 which continuously adjusts input voltage  $v_{in}$  such that  $\phi_p$ , rather than  $i_p$ , is kept at constant RMS value. Keeping the voltage amplitude of voltmeter 50 constant (by varying  $v_{in}$ ) keeps the amplitude of primary flux  $\phi_p$  constant. In this way local variations in inductance  $L$  around the circumference of the shaft do not cause variations in the primary flux  $\phi_p$ . The result is a circumferential induction  $B_{circ}$  and an axial induction  $B_{axial}$  which are virtually free of anomalies caused by surface inhomogeneities. Hence the output signal (from voltmeter 38) is essentially independent of RPM and considerably more accurate than existing devices. The output signal from voltmeter 38 is also of relatively constant amplitude within one mechanical cycle (for constant torque within one mechanical cycle) and therefore is suitable for detecting variation in torque virtually instantaneously.

In some instances this embodiment has an even simpler modification as shown in Figure 5B. For certain values of circuit parameters the feedback of the signal from voltmeter 38 does not have to be done. Note from (I) that time varying flux in the primary core 30 means voltage drop across the primary coil 32. There is internal resistance in the primary coil 32 as well, so the driving voltage  $v_{in}$  must equal the total of the inductive voltage  $-v_{coil}$  produced by time varying flux  $\phi_p$  of the primary coil 32 plus the voltage drop across the internal resistance  $R_p$  of the primary coil circuit. That is

$$v_{in} = -v_{coil} + R_p i_p = N_p \frac{d\phi_p}{dt} + R_p i_p \quad (IV)$$

When resistance  $R_p$  in the primary coil 32 is negligible (such as might be encountered with use of superconductor materials or with few windings in the primary coil 32), the second term in the right hand side of

(IV) can be assumed effectively zero. In that case the input voltage ( $v_{in}$ ) is equal and opposite to the primary coil voltage  $-v_{coil}$  associated with the oscillating primary flux  $\phi_p$ . Hence keeping input voltage  $v_{in}$  (rather than input current  $i_p$ ) at constant amplitude keeps primary flux amplitude  $\phi_p$  constant regardless of any non-uniformity in shaft magnetic properties.

Note that in this or any other embodiment the primary core/coil 30/32 can be aligned axially instead of circumferentially and the secondary core/coil 34/36 can be aligned circumferentially instead of axially. Further, even though the device performs optimally when the secondary and primary core/coils 34/36 and 30/32 are at right angles to one another and when one of the coil/cores is axially aligned, they can in fact be at any angle with respect to one another and with respect to the shaft axis.

The auxiliary coil 48 is depicted as wrapped around primary core 30 and concentric with primary coil 32, but all that is essential to the proper working of embodiment one is that a significant portion of the flux in the primary flux path of the shaft 20 pass through auxiliary coil 48. Hence auxiliary coil 48 can be wrapped inside of, wrapped outside of, wound along with, located elsewhere on primary core 30 than, or placed in close proximity to primary coil 32; or placed anywhere else so long as the signal obtained from auxiliary coil 48 or a function of that signal can be used to control the primary flux in the shaft 20.

The description of embodiment one contains many specificities, but embodiment one is not limited in scope by these specificities. Embodiment one is primarily a method to keep primary flux at effectively constant amplitude, thereby eliminating spurious signal components due to material inhomogeneities, temperature, and shaft speed. This can be accomplished utilizing an auxiliary coil as recited herein to determine primary flux or by any other suitable method or means such as, but not limited to, Hall effect sensing. Further, the determination of secondary flux can be accomplished with a secondary coil as described herein or by any other suitable method or means including, but not limited to, Hall effect sensing. In addition, primary flux can be controlled by passive control methods including, but not limited to, methods which incorporate additional circuit components such as capacitors, resistors, etc. in the primary circuit which serve to maintain primary flux at effectively constant amplitude. Embodiment one, therefore, encompasses any method which maintains primary flux at effectively constant amplitude and monitors torque via determination of secondary flux.

#### Embodiment 2: Divide Output Signal by Input Voltage

Figures 6A and 6B depict different variations of embodiment number two of the present invention. In embodiment number two the standard prior art approach is used for the primary circuit in which primary current  $i_p$  amplitude is kept constant. For the constant primary current  $i_p$  amplitude local variation in magnetic permeability  $\mu_{Fe}$  will be reflected in both the  $B_{circ}$  and the  $B_{axial}$  fields. Output voltage from secondary coil 36 depends on the time derivative of  $B_{axial}$  (see (I)).

In Figure 6A an auxiliary coil 52 around the primary core produces a voltage signal (measured by voltmeter 54) dependent on the time derivative of the primary  $B_p$  field (i.e., on  $\phi_p$ ). Both signals incorporate the local inhomogeneities, but only the output of the secondary includes changes due to torque induced stresses. Dividing the instantaneous secondary voltage produced by secondary coil 36 by the instantaneous auxiliary coil voltage measured by voltmeter 54 by means of signal divider 56 results in a signal measured by voltmeter 38 which is essentially free of inhomogeneity induced variation. The signal measured by voltmeter 38 nevertheless still depends directly on the applied stress in the shaft and is a good measure of instantaneous torque.

In practical application it may at times prove necessary to add a component to the circuit between voltmeter 54 and signal divider 56 which would convert instantaneous zero signal values (measured by voltmeter 54) to small finite values in order to preclude division by zero in signal divider 56.

As with embodiment #1, negligible resistance in primary coil 32 would result in the simplification of embodiment #2 shown in Figure 6B. With negligible primary coil 32 resistance  $R_p$ , voltage in the primary coil 32 itself can be used directly to divide into the voltage from the secondary coil 36, thereby eliminating the need for auxiliary coil 52 on the primary core.

As with embodiment one, the primary core/coil 30/32 can be aligned axially instead of circumferentially and the secondary core/coil 34/36 can be aligned circumferentially instead of axially. Further, even though the device performs optimally when the secondary and primary core/coils 34/36 and 30/32 are at right angles to one another and when one of the coil/cores is axially aligned, they can in fact be at any angle with respect to one another and with respect to the shaft axis.

The auxiliary coil 52 is depicted as wrapped around primary core 30 and concentric with primary coil 32, but all that is essential to the proper working of embodiment two is that a significant portion of the flux in the primary flux path of the shaft 20 pass through auxiliary coil 52. Hence auxiliary coil 52 can be wrapped inside of, wrapped outside of, wound along with, located elsewhere on primary core 30 than, or placed in close proximity to primary coil 32; or located anywhere so long as the signal obtained from auxiliary coil 52 or a function of that signal can be used as a meaningful input to signal divider 56.

Although Figures 6A and 6B and the above discussion relates to a division of the signal produced by secondary coil 36 by either the signal produced by auxiliary coil 52 or primary coil 32, embodiment two equally relates to a division of the signal produced by auxiliary coil 52 or primary coil 32 by the signal produced by the secondary coil 36. Further, the signals divided can be instantaneous, RMS, amplitude or any other indicator of



signal strength.

The description of embodiment two contains many specificities, but embodiment two is not limited in scope by these specificities. Embodiment two is primarily a method to eliminate spurious signal components due to material inhomogeneities, temperature, and shaft speed by dividing two signals each of which contain similar such spurious signal components, but only one of which contains a torque dependent component. These signals can be obtained as recited herein using one or more coils to measure flux levels but the method is not restricted to use of such coils. Other methods for determining flux such as, but not limited to, Hall effect sensing could be used as well. Embodiment two, therefore, encompasses any method which accomplishes division of two signals such as those described herein whether or not coils are used to obtain those signals.

#### Concomitant Solutions to Variation in RPM, Temperature, Drift Problems

Spurious material non-uniformity induced frequency components of the output voltage signal from secondary coil 36 are directly dependent on shaft speed. Via embodiment #1 or #2, the spurious frequency components are eliminated from the output signal measured by voltmeter 38 and dependence of the output signal of voltmeter 38 on shaft speed is minimized and reduced to an inconsequential level.

Temperature dependence in both embodiments is minimized as well. In embodiment #1 variations due to temperature dependent permeability and mechanical tolerances will automatically be compensated for by keeping the primary flux  $\phi_p$  amplitude constant. In addition, thermal variations in wire resistivity would not give rise to differences in secondary voltage measured by voltmeter 38 since the secondary circuit is open circuit.

In embodiment #2, both voltage signals entering signal divider 56 are affected by temperature and tolerance variation in the same way and hence when the signals are divided, variation caused by temperature and tolerances drops out of the resulting signal measured by voltmeter 38.

Although drift in signal is not a serious problem since it can always be "nulled out" prior to measurement, it should be noted that drift, particularly in embodiment two is reduced as well. Drift affects both signals entering signal divider 56 in a similar way, and hence, when they are divided, effects from drift are minimized.

#### Embodiment 3: Multiple Sensors to Solve Misalignment, Bending Stress Problems

Figure 7 illustrates a modification which eliminates spurious output signal caused by shaft bending stresses and/or shaft misalignment and which is applicable to any embodiment.

The inductance L is dependent on the air gap dimension. For shaft displacement from centerline due to slight misalignment or bending, the inductance L will change and hence so will the output signal (even for the embodiments presented above). In addition, stresses from bending will affect permeability (magnetostriction again) and further alter the output. Both of these effects contribute erroneous components to the output signal which are sinusoidal with period equal to the time of one shaft revolution.

This problem can be ameliorated in either of two ways:

- 1) Place sensor in an end or main bearing where no bending stress exists and misalignment can be minimized. (Note that though this is not specifically claimed as part of the invention described herein, the invention and any of its embodiments described herein can be used in any location along a shaft including the end or main bearing. The reader will understand that a specific location cannot be claimed as a patent right.)

- 2) Use two sensors 66A and 66B on opposite sides of the shaft as in Figure 7 and add the two (instantaneous) signals  $v_A$  and  $v_B$ . For simplicity Figure 7 is shown with zero applied torque although the method is applicable with torque of any magnitude.

Method 2) above works because the misalignment and bending stress signal aberrations are  $180^\circ$  out of phase and so cancel one another when added. This second method has the added advantage of doubling effective signal strength (i.e., the sensitivity).

Method 2) functions optimally when sensors 66A and 66B are on opposite sides of the shaft. The sensors can, however, have any angular relation to one another as long as proper phase corrections are made to one or both signals to correct for the variation from  $180^\circ$  angular spacing between sensors. Further, embodiment three relates to any orientation of the sensors which is sufficiently close to  $180^\circ$  angular separation such that the sensor signals can be added directly without phase shifting to achieve a sufficiently accurate signal.

While the discussion of embodiment three relates to a single pair of sensors, any number of pairs may be employed. Alternatively, a group of more than two sensors could be used in which signals from all sensors are added to obtain a resultant signal free of misalignment and bending stress induced components. For example, signals from three sensors spaced  $120^\circ$  apart, or sufficiently close to  $120^\circ$ , could be directly summed. For spacing other than  $120^\circ$ , signal phase shifting can be done where necessary before summation.

#### Solutions to Mass Production and Recalibration Problems

The reader will note that the invention solves the problems of RPM dependence, temperature dependence,

and non-instantaneous torque measurement in a simpler, more elegant, and more effective manner than do prior art devices. At the same time the present invention solves the heretofore intractable problems of impracticability for mass production and need for periodic recalibration during the lifetime of the shaft. It does this because unlike prior art, the correction methodologies of this invention are independent of the particular properties (magnetic, residual stress, tolerance, and misalignment) of each particular shaft. In embodiment one, for example, the primary induction B and hence the secondary coil voltage (measured by voltmeter 38 in Figures 5A and 5B) are kept independent of shaft properties regardless of what those particular properties may be. The user never has to concern himself or herself with determining the RPM correction for each particular shaft and applying that correction to the output signal. Nor does recalibration have to be done as shaft properties change over time, since the circuitry of embodiment one automatically takes these changes into account, i.e., it automatically eliminates spurious signal components regardless of their nature or degree.

Embodiment two has the same advantages as embodiment one. The two signals entering signal divider 56 are both affected by shaft properties in the same way, regardless of what those properties may be in any given shaft. Hence the signal read by voltmeter 38 will not depend on variations from shaft to shaft or on changing of shaft properties over time.

Embodiment three is also amenable to mass production because it solves the misalignment and bending stress problems in a manner which is independent of individual shaft bending or misalignment. Changes in alignment and bending stress over time will also automatically be accounted for.

#### Advantages Over Prior Art

This invention can thus be seen to solve virtually all of the problems delineated in the "Description of Prior Art" section presently associated with determination of torque in rotating shafts in a much more complete, accurate, simple, economic, and straightforward manner than any previous art.

While the above description contains many specificities, the reader should not construe these as limitations on the scope of the invention, but merely as exemplifications of preferred embodiments thereof. Those skilled in the art will envision many other possibilities that are within its scope. For example any of the embodiments can use any materials, including superconductors, for any components, and can have any dimensions or shapes. The air gaps can be of any dimensions and can even be of non-constant or non-uniform gap width. The shaft 20 can be rotating or stationary and of any suitable material, size, or shape. The shaft does not even have to be cylindrical and can have one or more strips of material attached to it which enhance the working of the invention. The strips can be of any suitable material including thin films and can be attached to any amount of the shaft. Further, the shaft or any attachments to it may be treated to minimize random anisotropy effects. Such treatments include, but are not limited to, vibration shaking, scoring of the surface, knurling, grinding, mechanical or laser scribing, shot peening, sand blasting, heat treatments, torsional or axial overstraining, rolling, chemical treatments, and electromechanical treatments. Also, it is not necessary that the torque be transmitted through a shaft and any torque transmitting element may be used.

Though the embodiments herein recite the use of coils to obtain signals dependent on particular fluxes, any other method or means which measures flux such as, but not limited to, Hall effect sensing, can be used as well in any of the embodiments. In any embodiment where one or more coils are used, any number of coil windings can be used for any of the coils in any of the embodiments and the cores can have any suitable shape and size as well as be of any suitable material. The cores do not have to be ferromagnetic and can, if for instance the wires are superconducting, be made of air, any gas, any other material, or even a vacuum. Additionally, wherever one coil is indicated (such as, but not limited to, the primary coil) a plurality of coils could be employed. If any other device such as, but not limited to, a Hall effect sensor is used in lieu of a coil pickup, then a plurality of such other devices could also be used. Also, whereas AC sinusoidal current is probably the most suitable for the invention, any wave form current/voltage can be used, even DC or a pulse with appropriate integration/differentiation. Wherever constant amplitude of any signal is referred to, any nearly constant amplitude signal which results in an acceptable measure of torque will suffice. Further, any signal does not have to be used directly but can be amplified or transformed in any manner and the resultant amplified or transformed signal can be used for the same or similar purpose as the original signal. Also, any signal (e.g. voltage) does not have to be measured directly, but can be determined indirectly via measurement of parameters which are related to such a signal (e.g., measuring other voltages in a loop, measuring current when impedance is known, etc.). Of course, all arrangements where voltmeters with one side attached to ground measuring the non-grounded side of a circuit can equivalently be arranged where the same voltmeters measure voltage across the circuit with neither side grounded. The converse is true as well. Although the term voltmeter is used, any means to measure or determine voltage can be employed; and although terms such as oscillator and power amplifier are used, any devices which serve the same or similar purposes for them or any other system components can be employed as well. Further, the sensors can be located anywhere along the shaft axially, radially, or at the ends, in any number, and can even be used with a torque disk such as that described in U.S. Patent 4,697,460 rather than such appendage to the shaft. Also, any of the embodiments can be used separately or in combination in any degree with any of the others. Finally, the invention in any of its embodiments can also be used as a device to measure stress and strain, as in U.S. Patent 2,912,642, and can even be used to measure force applied to any given object or objects. Accordingly, the scope of the invention

should be determined not by the embodiments illustrated, but by the appended claims and their legal equivalents.

## Claims

1. That whereas previous magnetostrictive methods for sensing torque induce a primary magnetic induction field flux in a torque transmitting element (20) and obtain a secondary signal which depends on a secondary magnetic induction field flux in said torque transmitting element (20) whose secondary magnetic field direction arises at a non-zero angle from the primary magnetic field as a result of magnetostriction when torque is transmitted by the torque transmitting element (20), and said secondary signal is a function of torque transmitted plus non-torque induced causes such as inhomogeneity in magnetic permeability of the torque transmitting element (20), the improvement (Figures 5 to 7) is characterized by:
  - obtaining an auxiliary signal which depends on the primary magnetic induction field flux and which is a function of non-torque induced variations in magnetic permeability in said torque transmitting element (20), and
  - using the auxiliary signal to modify the secondary signal such that a resultant signal obtained from such modification is dependent on torque yet is minimally affected by non-torque induced variations in magnetic permeability, whereby the resultant signal is thereby used to determine the torque transmitted.
2. The method for sensing torque of claim 1 wherein using the auxiliary signal to modify the secondary signal (Figures 5A and 5B) is characterized by:
  - maintaining the auxiliary signal at effectively constant amplitude such that the primary magnetic induction field flux is maintained at effectively constant amplitude,
  - whereby the secondary signal is thereby modified such that it is dependent on torque yet is minimally dependent on non-torque induced variations in magnetic permeability.
3. The method for sensing torque of claim 2 wherein the primary magnetic induction field flux is induced by at least one primary coil (32) of any number of turns, and maintaining the primary magnetic induction field flux at effectively constant amplitude (Figure 5A) is characterized by:
  - using associated electric circuitry to control the primary magnetic induction field flux such that the auxiliary signal from any type of flux sensing method such as, but not limited to, at least one auxiliary coil (48) which detects a significant amount of the primary magnetic induction field flux is maintained at effectively constant amplitude; and obtaining a secondary signal which depends on the secondary magnetic induction field flux is characterized by:
  - utilizing any method of flux sensing such as, but not limited to, at least one secondary coil (36) which detects a significant amount of secondary magnetic induction field flux and which produces the secondary signal which is a function of said significant amount of secondary magnetic induction field flux, whereby said secondary signal is used to determine the transmitted torque.
4. The method for sensing torque of claim 2 (Figure 5B) wherein the primary magnetic induction field flux is induced by primary electric circuitry and at least one primary coil (32) of any number of turns and of such low electrical resistance that any method for determining a primary circuitry parameter such as, but not limited to, primary voltage across at least one said primary coil (32) is a sufficiently accurate approximation to and a substitute for any method for determining an auxiliary circuitry parameter such as, but not limited to, voltage across at least one auxiliary coil (48) through which a significant amount of the primary magnetic induction field flux passes such that said primary circuitry parameter is controlled, thereby enabling the primary magnetic induction field flux to be maintained at sufficiently accurate approximate constant amplitude.
5. The method for sensing torque of claim 2 wherein maintaining the primary magnetic induction field flux at effectively constant amplitude is characterized by:
  - using associated electric circuitry for passive control of the primary magnetic induction field flux such that the primary magnetic induction field flux is maintained at effectively constant amplitude.
6. The method for sensing torque of claim 1 wherein using the auxiliary signal to modify the secondary signal (Figures 6A and 6B) is characterized by:
  - division of one of said signals by the other said signal (56),
  - whereby a resultant signal produced by said division is minimally affected by non-torque induced variations in the torque transmitting element (20) and said resultant signal is thereby used to determine the torque transmitted.
7. The method for sensing torque of claim 6 wherein the primary magnetic induction field flux is induced by at least one primary coil (32) of any number of turns (Figure 6A), and obtaining the auxiliary signal which depends on the primary magnetic induction field flux strength is characterized by:
  - using any method of flux sensing such as, but not limited to, at least one auxiliary coil (52) which detects a significant amount of the primary flux, and
  - obtaining the secondary signal is characterized by:
  - utilizing any method of flux sensing such as, but not limited to, at least one secondary coil (36) which detects a significant amount of secondary magnetic induction field flux and which produces the

secondary signal which is a function of said significant amount of secondary magnetic induction field flux, whereby division of one of said signals by the other said signal produces the resultant signal and the resultant signal is used to determine the torque transmitted.

8. The method for sensing torque of claim 6 (Figure 6B) wherein the primary magnetic induction field flux is induced by a primary electric circuit and a primary coil (32) of any number of turns and of such low electrical resistance that any means for determining a primary circuit parameter such as, but not limited to, voltage across said primary coil (32) is a sufficiently accurate approximation to and a substitute for any means for determining an auxiliary circuit parameter such as, but not limited to, voltage across an auxiliary coil through which a significant amount of the primary magnetic field flux passes such that said primary circuit parameter is used to yield a sufficiently accurate approximate primary signal which is used as the auxiliary signal in the division with the secondary signal to yield the resultant signal.

9. The method for sensing torque of claim 1 wherein the torque transmitting element (20) is modified by any method which can minimize random anisotropy in magnetic permeability such as, but not limited to, vibrational shaking, such that the resultant signal is affected minimally by magnetic anisotropy.

10. A plurality of individual torque sensing methods (Figure 7), each of which is such as the torque sensing method of claim 1 (66A, 66B), which is characterized by a misalignment signal correcting method for sensing torque wherein

the individual torque sensing methods (66A, 66B) are used in various locations around the torque transmitting element (20) wherein, if the angular spacings between said locations are effectively equal, the individual torque sensing output signals of each of said plurality of individual torque sensing methods are added to obtain a resultant signal, and if the angular spacings between said locations are not effectively equal, the individual torque sensing output signals of each of said plurality of individual torque sensing methods are phase shifted and then added to obtain the resultant signal,

whereby said resultant signal is used to determine torque, and said resultant signal is minimally affected by bending stress and misalignment of the torque transmitting element (20).

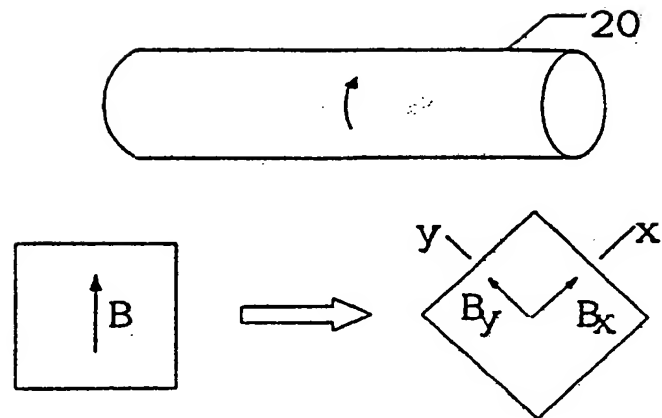


FIGURE 1A

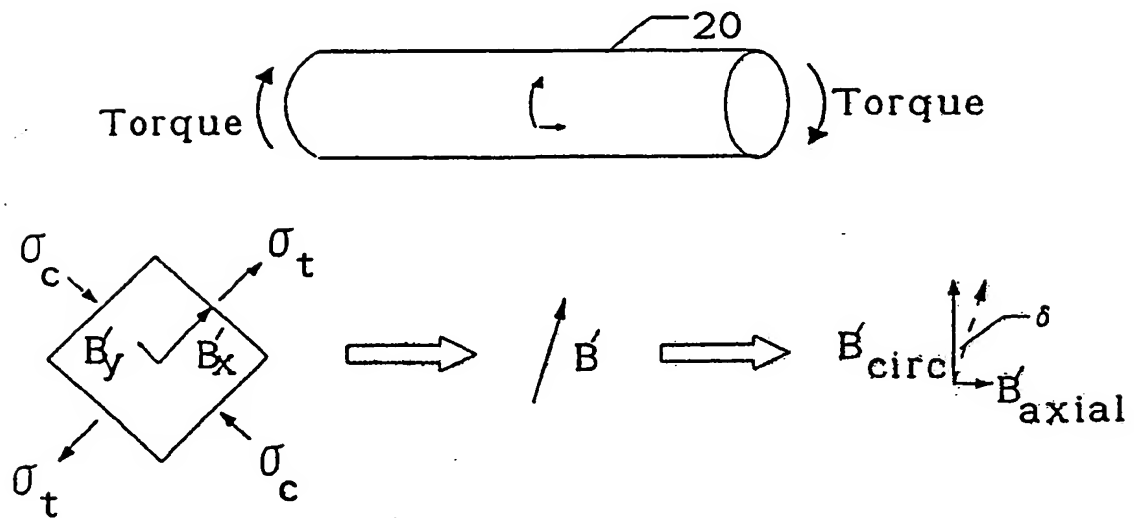
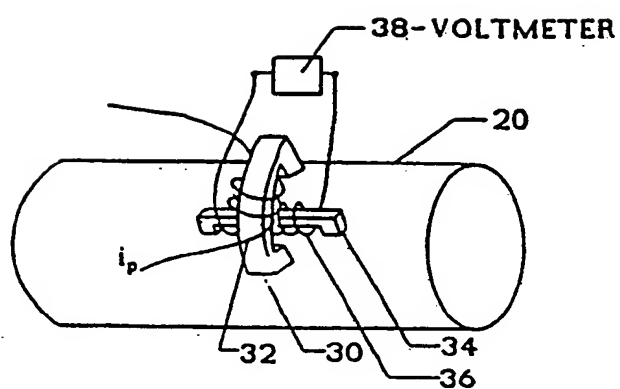
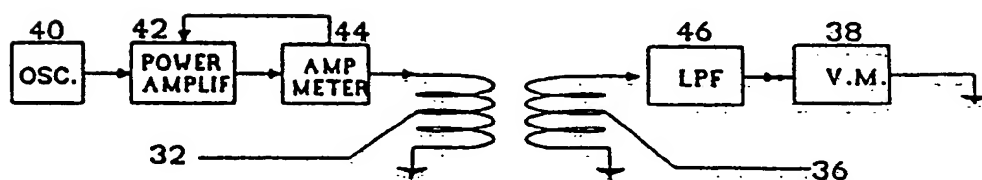


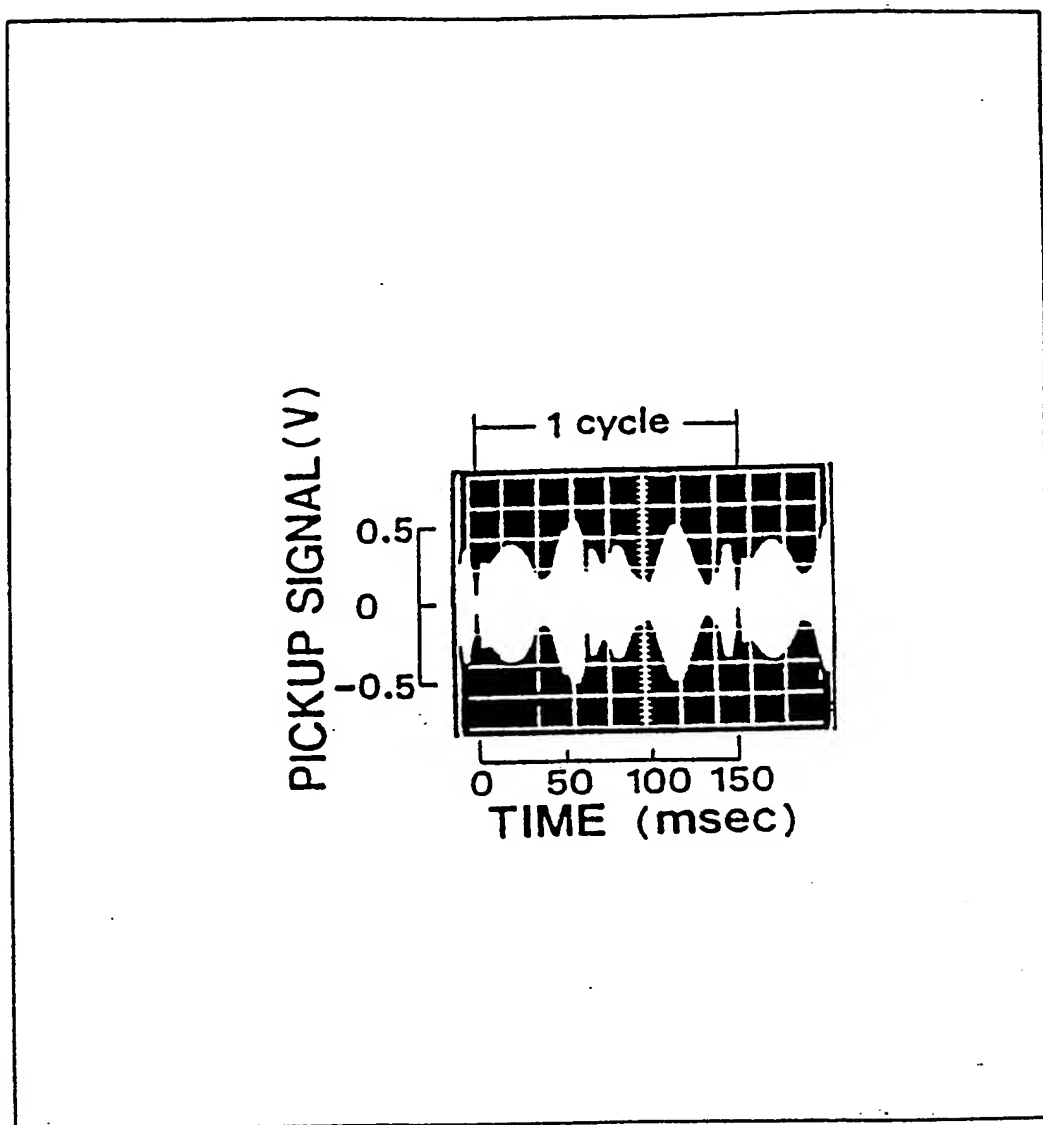
FIGURE 1B



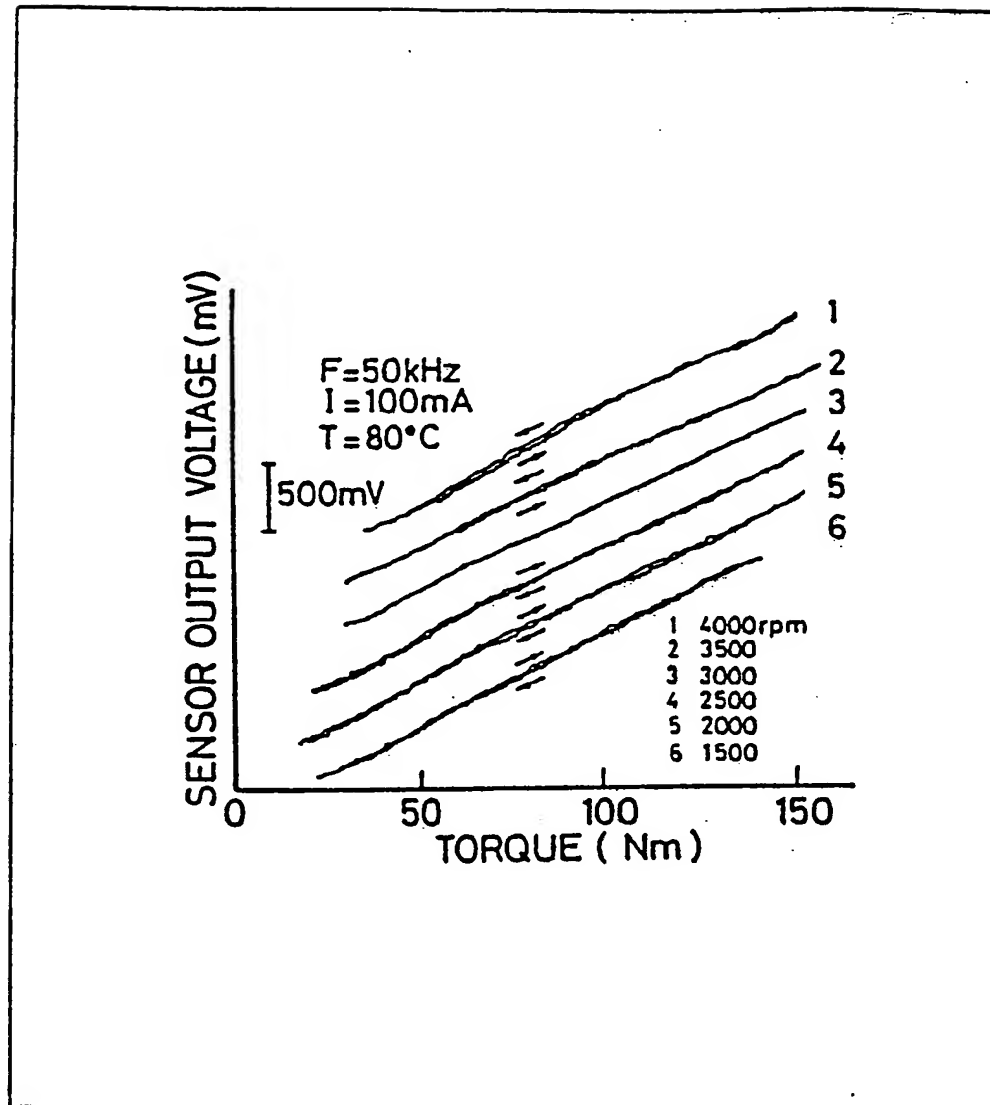
**FIGURE 2A: PRIOR ART**



**FIGURE 2B: PRIOR ART**

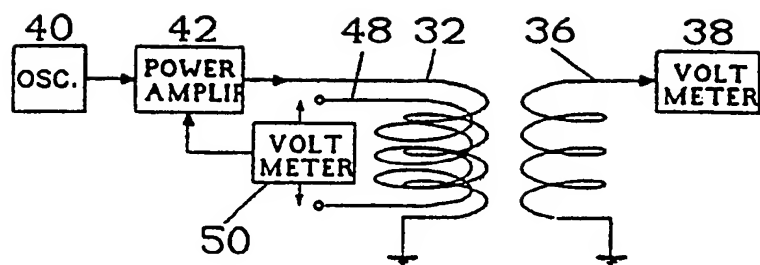


**FIGURE 3: PRIOR ART**

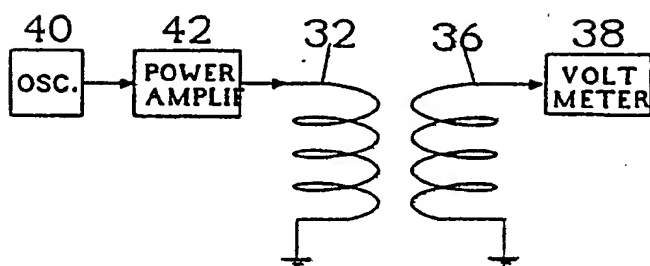


**FIGURE 4: PRIOR ART**





**FIGURE 5A**



**FIGURE 5B**

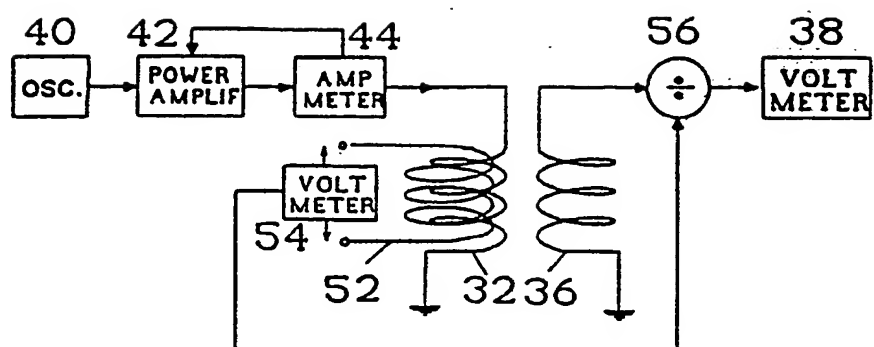


FIGURE 6A

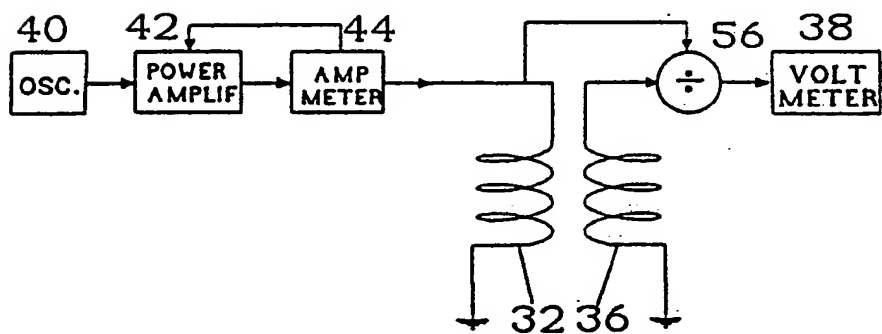
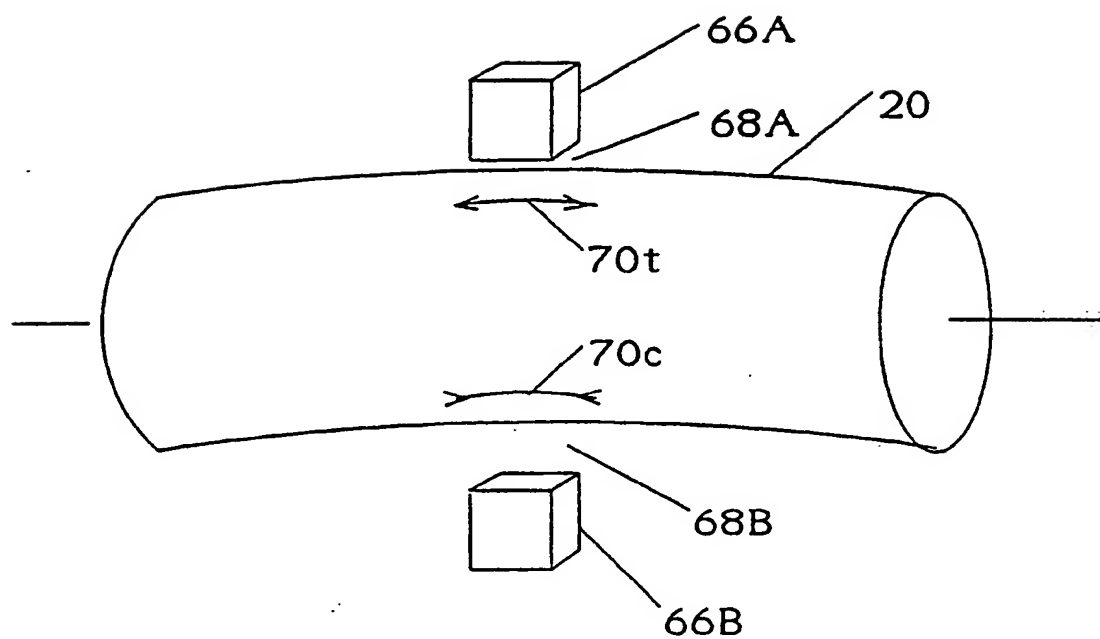


FIGURE 6B



**FIGURE 7**



European Patent  
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# EUROPEAN SEARCH REPORT

Application Number

EP 89 40 2052

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 5)
X,Y	DE-C-3 206 503 (LICENTIA PATENT-VERWALTUNGS-GmbH) * Abstract; column 4, lines 9-49; figure 2 * ---	1	G 01 L 3/10
X,Y	DE-A-3 511 442 (INTERNATATIONAL FLUGGERÄTE UND MOTOREN GmbH) * Abstract; page 9, lines 6-25; page 8; page 9, lines 1-4; figures * ---	1-3,5-7	
Y	US-A-4 716 773 (Y. NONOMURA et al.) * Abstract; column 2, line 40 - column 5, line 16; figures * ---	1	
X	DE-A-3 437 379 (BENTLY NEVADA CORP.) * Abstract; page 13, lines 12-33; page 14, lines 1-4; figure 1 * ---	10	
X	PATENT ABSTRACTS OF JAPAN, vol. 10, no. 256 (P-493)[2312], 2nd September 1986; & JP-A-61 83 927 (TOSHIBA CORP.) 28-04-1986 * Abstract * ---	10	
Y	US-A-2 365 073 (N.L. HAIGHT) * Page 2, left-hand column, lines 23-40; figure 1 * -----	1	
The present search report has been drawn up for all claims			
Place of search THE HAGUE		Date of completion of the search 17-10-1989	Examiner VAN ASSCHE P.O.
<b>CATEGORY OF CITED DOCUMENTS</b>			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons ----- & : member of the same patent family, corresponding document	

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